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Analysis of Orientation, Bond Thickness, and Bond Force of a Single Layer Cubic Boron Nitride Grinding Grain

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Saint-Gobain: Analysis of Orientation, Bond Thickness, and Bond Force of a Single Layer Cubic Boron Nitride Grinding Grain

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By

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Liaison: Saint-Gobain

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Approved:

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Abstract

Currently, Saint-Gobain Abrasives team uses the Chemical Mechanical Planarization (CMP) process to manufacture multiple products. Cubic Boron Nitride grain orientation has not been optimized which could increase the life of the conditioning pad integral to the CMP process. Our team designed a set of experiments to obtain the optimal grain angle to increase the maximum bonding force thus increasing the life of the conditioner tool. We analyzed each new angle and assembled a final optimal grain orientation.

Acknowledgements

We would like to thank multiple people for their assistance and guidance throughout the course of this project. Firstly, we would like to thank our advisor Professor Kevin Rong of Worcester Polytechnic Institute for providing us with guidance throughout the project and the opportunity of complete our Major Qualifying Project in China. We would also like to thank Zhi Geng, Tianxing Zhu, Dr. Zhang of Shanghai University, and Professor Xuekun Li of Tsinghua University for their support and expertise throughout the course of the project.

Authorship

Throughout this Major Qualifying Project Nathaniel Yuhas and Francis Ascioti completed the majority of the software work required to complete the objectives of this project. Nathaniel Yuhas focused on the SolidWorks modeling and response surface method software. Francis Ascioti concentrated on the finite element software. Both partners focused their efforts on different software in order to select suitable programs.

The report was jointly written by both WPI partners.

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Introduction

Chemical Mechanical Planarization (CMP) is a process utilized to create wafers used in electronic products such as computers and cellular phones (Steigerwald, *Chemical mechanical* 1). The process uses both chemical and mechanical components to create a smooth and even surface. Typically, a Cubic Boron Nitride (CBN) grain is placed in on a pad that is used to scratch the surface of a polymer pad where a specific slurry containing grit and chemicals is held. On this surface is where a wafer will be planarized (Steigerwald 2).

CMP involves a variety of factors that affect the longevity of the conditioning pad through the bonding force between the CBN grit and its bonding layer. Factors include bond layer thickness, grain orientation, size of grain, grain shape, and pressure of the pad. The goal of this project was to optimize the bonding force for the CMP conditioner pad and CBN grit by changing the orientation angle of the CBN grit.

A higher bonding force will result in a longer lasting pad which will increase the efficiency of the process and lower the cost due to the use of less conditioning pads. The final results of this study is a series of optimized three dimensional angles with maximized bonding forces.

Background

In order to understand the scope of the project, researching the history of Saint-Gobain was necessary. The background section contains Saint-Gobain history, modern Saint-Gobain, and an overview of the CMP process.

Saint-Gobain in the Past and Present

Saint-Gobain: The Beginning

Saint-Gobain has an extensive history of being a large multi-national producer of various industrial materials. These materials range from glass windows for buildings to the micro-chips inside of computers and cell phones. Saint-Gobain was founded in France in 1665. The company began as a small mirror manufacturer, and in less than a decade, became a leader among its peers (Saint-Gobain Group, Our History, 2013). In 1853, the company opened its first international site located in Mannheim, Germany (Saint-Gobain Group, Our History, 2013). This trend would continue with Saint-Gobain becoming an international company. Saint-Gobain began its diversification as it began to manufacture glass as well as mirrors (Saint-Gobain Group, Our History, 2013).

Saint-Gobain played a major role in research from its foundation in the glass manufacturing field. In the early 20th century, the company developed many new glassmaking techniques, including a process that would reduce the shattering of automotive glass[i] (Saint-Gobain Sekurit, 2013). Other techniques have included coating glass with aluminum and the bending of glass which is still one of the company's' major products (Saint-Gobain Abrasives, 2013). The latter is becoming an important role in the smartphone industry, as new curved touchscreens are coming to the market (Lu, K., 2013).

The Past Few Decades

In the mid-20th century, Saint-Gobain experienced a substantial expansion as profits continuously increased ten percent for nineteen consecutive years. Along with profit expansion, Saint-Gobain also increased their workforce from just under forty thousand to over one-hundred thousand in the same amount of time. The expansion of the company also reached countries including China, the United States and many other countries (Saint-Gobain Group, Our History, 2013). In 1993, Saint-Gobain acquired the former leading abrasives manufactures in the USA (Saint-Gobain Group, Our History, 2013). This company, Norton, was well over one-hundred years at the time and is still the world-leader in abrasives providing solutions for industrial manufacturing/maintenance, auto repair, construction, and the home improvement market (Norton Abrasives, 2013).

Saint-Gobain now has over fourteen research centers throughout the world and between the years of 2009-2011, has been granted 117 patents in North America alone. The patents granted in North America have applications in the areas of defense, oil exploration, renewable energy, medical imaging, abrasives and others (Saint-Gobain-North America, 2011).

Saint-Gobain Organization

Saint-Gobain Locations and Products

Saint-Gobain has headquarters in the United States, Canada, and France. The company has locations in nearly every state in the U.S. and has operations in 64 countries (Saint-Gobain, 2013). The products offered by Saint-Gobain are divided into five departments. These departments include: Innovative Materials, High-Performance Materials, Building Distribution, Construction Products and Packaging.

The Innovative Materials department is supported by two dedicated research centers, one in Germany and the other in France. Having more than 33,000 people in 42 countries, the sub-department of Flat Glass is the leading flat glass manufacturer in Europe and number two worldwide(Saint-Gobain Innovative Materials, 2013).Other sub-departments of the Innovative Materials department include processing and distribution of glass for the building industry, automotive glazing and solar energy solutions.

The second major department of Saint-Gobain is the High-Performance Materials department which is divided into three main types of materials – mineral ceramics (which includes abrasives), performance polymers and glass fabrics for the construction and manufacturing industries. The High-Performance Materials Activity "allocates a high proportion of net sales to research and development (3.8% in 2012) (Saint-Gobain 2012 Registration Document, 2012). Some of the examples of these large products include ceramic fuel cell technology and ceramic systems for storing the heat generated by solar concentrators (Saint-Gobain 2012 Registration Document, 2012).

The third major department of Saint-Gobain is the Construction department. "With more than 47,000 employees, industrial facilities in 55 countries and sales operations in 68 countries, the Construction Products Sector is the worldwide leader in interior and exterior building solutions (Saint-Gobain 2012 Registration Document, 2012). Some of the products from this department include insulation, pipes, and industrial mortars (Saint-Gobain 2012 Registration Document, 2012).

The last two major departments are the smaller of the five departments. These include the Building Distribution department and Packaging department.

Saint-Gobain Economics

A breakdown of their sales can be seen below.

(in € millions)	2012	2011
NET SALES	**43,198**	**42,116**
Operating income	2,881	3,441
Consolidated net income	796	1,360
Recurring net income(1)	1,126	1,736
Recurring earnings per share (in €)(1) (2)	2.12	3.24
Net income attributable to equity holders of the parent	766	1,284
Earnings per share (in €)(2)	1.44	2.40
Total investments(3)	2,127	2,638
Consolidated equity (including minority interests)	17,851	18,218
Net debt	8,490	8,095
Non-current assets	29,629	29,877
Working capital	4,238	3,161

(1) Excluding capital gains and losses on disposals, asset write-downs and material non-recurring provisions.
(2) Earnings per share are calculated based on the number of shares outstanding at December 31.
(3) Capital expenditure and financial investments, excluding share buybacks.

Figure 1 Saint Gobain Sales in (million of €)

The overall income is coming in from mainly Western European countries with about 33%, while France's incomes are 22%. North American markets are pulling in 24% and the rest are from emerging countries and Asia (Saint-Gobain 2012 Registration Document, 2012).

Chemical Mechanical Planarization

Before CMP

Before CMP became a player in the micro abrasive industry, one major process was used. This process used boron phosposilicate glass (BPSG) deposition which was followed by a BPSG anneal. This process had multiple steps including technologies like spin-on-glass technology, followed by curing the SOG and removing remaining solvent and organic components. The smaller the requested resolution using these very difficult and long-processes, the longer it took to create such wafers. However, even though this was the most used process of abrasive companies, the layer was never fully planarized, unlike CMP. There was a substantial need for something more efficient, something that could do these multiple difficult processes all in one go. This is where the need for CMP stemmed from.

CMP Process

The CMP process can be described by figure 2.

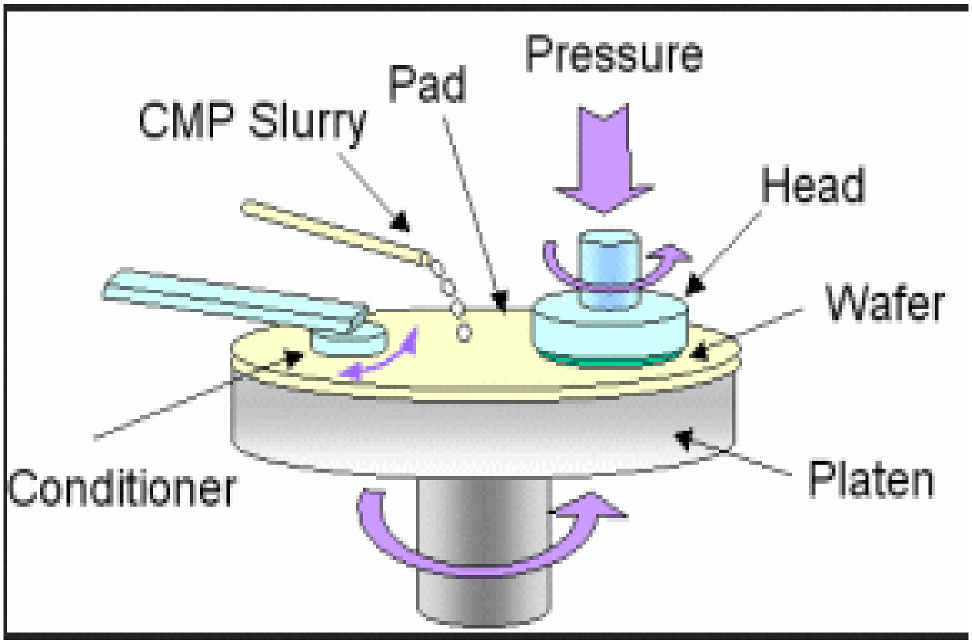

Figure 2 CMP Diagram

However for the process, the steps include the following (Banerjee, G. & Rhoades, R. L., 2008):

1. Deposit desired film onto the device side of wafer
2. Load unprotected wafer onto the head (device side down)
3. Flow slurry (mixture chemicals and trillions of suspended particles) onto large diameter rotating polymer pad
4. Lower conditioner to pad, this cuts the pad allowing the slurry to fill the gaps
5. Lower wafer onto pad and apply a controlled pressure ranging from roughly 50 lbs. to several hundred pounds
6. Polish until sufficient amount of the wafer has been removed
7. Remove any debris left behind on the wafer surface

CMP Tool

CMP tools differ in size depending on the product, whether it be glass or silicon wafers. However the same process is utilized. The tool itself consists of a rotating platen which is covered by a pad, which is most commonly a polymer. The wafer, which is the product being planarized, is placed face down towards the pad. A retaining ring holds this wafer in place so that no vibration or movement occurs during the process. Also on the pad is the pad conditioner, usually a steel pad with diamond or cubic boron nitride layered along the surface of the conditioner. This is attached to an arm that will apply downward force on the pad to perform work on the pad. Lastly, there is an arm over the pad that will apply the slurry during the process which is what does work on the wafer. The figure below shows the basic diagram of the tool.

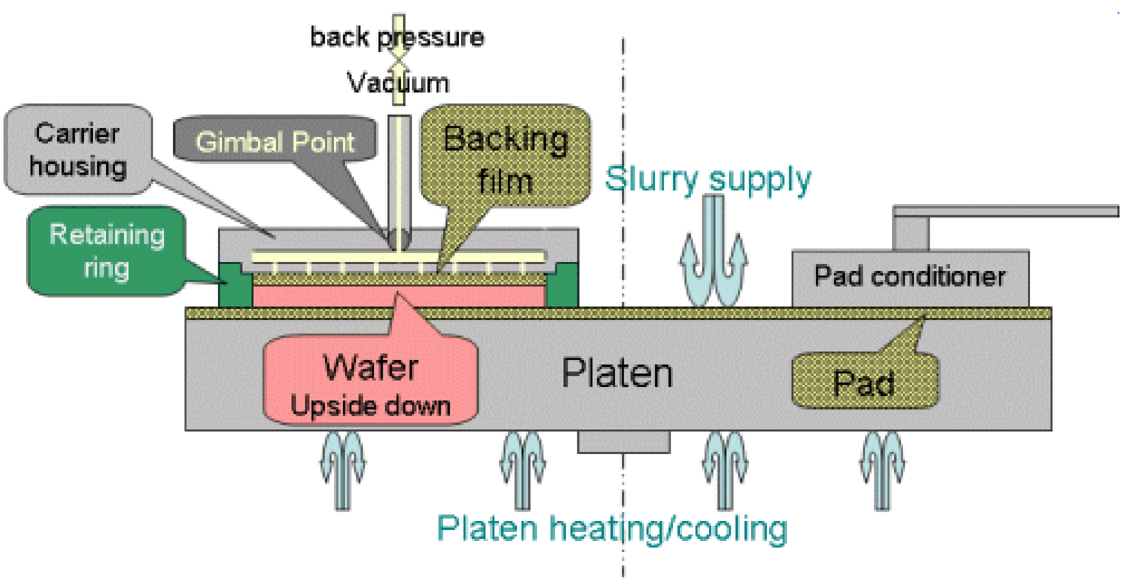

Figure 3 Diagram of Conditioning Pad

The problem was identified as a lack of longevity with the current conditioner pad. In order to make the conditioner pad last longer, analysis of the orientation angle needed to be done in order to see if there is an optimal orientation angle. In addition to this, the conditioner pad replacement procedure is time consuming which limits the amount of product to be produced. When a conditioner pad fails, individual grains are displaced from the conditioning pad rendering the product useless. Conditioning pads that have greater longevity will result in more useable product over a given time.

Methodology

The following objectives were used to reach the project goal. First, the problem was identified which allowed for the creation of an experiment design. The experiment order at the most basic level can be seen by Figure 4. Each step will be described in more detail below.

Figure 4 Flow Chart of Basic Methodology Steps

Model Creation in SolidWorks

The experiment design required multiple models in computer animated drawings. SolidWorks was chosen for the models due to its compatibility with most software as well as the efficiency at which orientation angles could be adjusted. The following procedure was followed:

1. Creation of the bonding layer
2. Creation of the CBN grain
3. Embedding the CBN grain in the bonding layer
4. Adjusting the CBN grain for each required orientation angle

Obtaining Bonding Force in ANSYS

With these drawings, Finite Element Method (FEM) software was utilized to obtain bonding force results due to change in orientation angles. Under the direction of the project advisors ANSYS was chosen due to the same software being used for similar past projects. The following number points describes the procedure followed in ANSYS:

1. Import SolidWorks Model
2. Input Element Type
3. Input Material Properties
4. Mesh the Model
5. Create the Contact Pair Between the Two Models
6. Add in a Force and Constraints

7. Solve the Model

Analyzing Bonding Force in Design Expert

Upon obtaining bonding forces, the values were inputted into a Response Surface Methodology (RSM) program. The software provided the required grain orientation angles and the user inputted the bonding forces obtained in the ANSYS software. This RSM software allowed us to find a relationship between orientation angles and bonding force. It was appropriate to use Design Expert because of the ability to employ a RSM face centered analysis.

Results

Modeling CBN Grain and Bonding Layer

The first step in the experiment required fourteen models to be created. SolidWorks was chosen as the computer animated software due to its compatibility with ANSYS software. The models were built with the parameters of a bonding layer thickness of 300 micrometers, and a grain diameter of 341 micrometers. A reference plane was also created in each model to keep an average 67% grain height off of the bonding layer. Building an accurate and precise model in this program allowed for us to move the experiment forward by importing these models into a FEM software. Figure 5 is an example of one of the models created in SolidWorks with a certain orientation angle. Figure 6 is an example of how the orientation angle can be changed in SolidWorks. This process was completed for each CBN Grit then combined with the bonding layer template seen in Figure 5. Figure 7 is the method employed to change the lead, orientation, and shear angles efficiently.

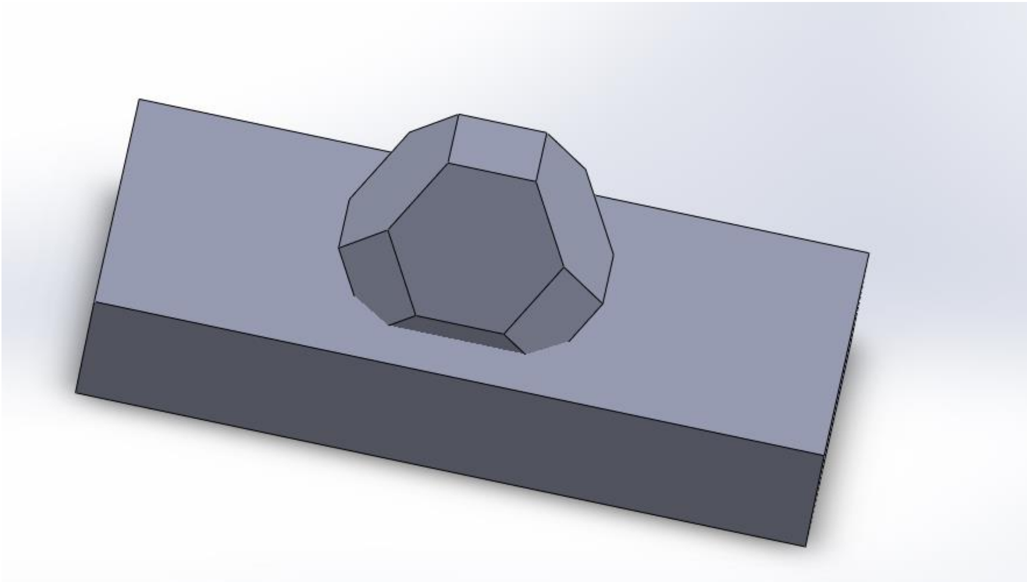

Figure 5 SolidWorks CBN Grit and Bonding Layer Model

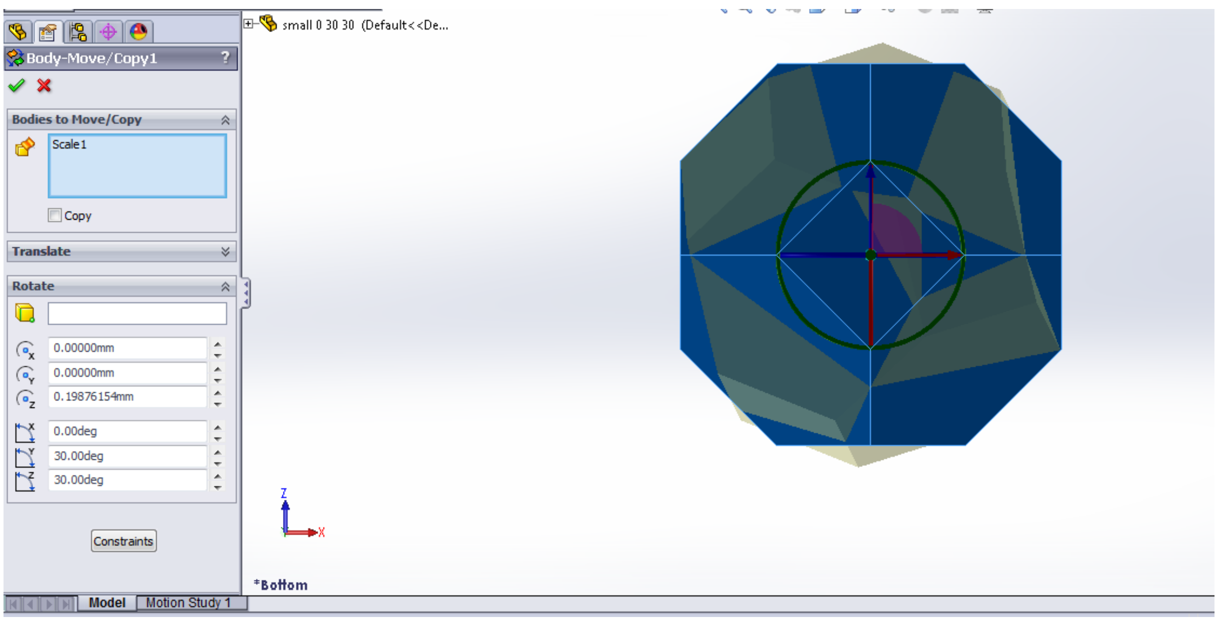

Figure 6 Example of Changing Orientation Angle in SolidWorks

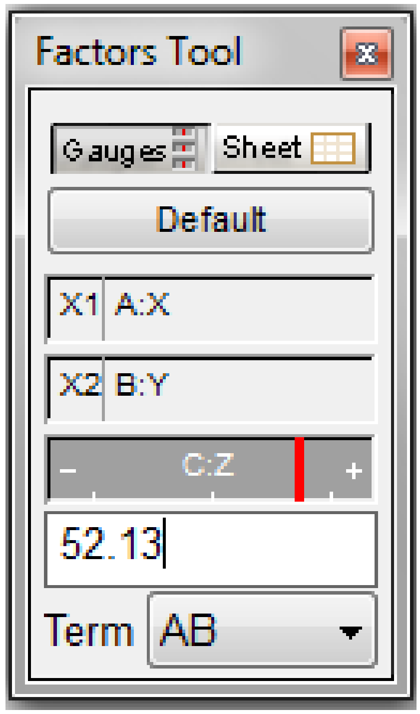

Figure 7 SolidWorks: Angle Input

Finite Element Method Software

In order to effectively and accurately obtain results, the SolidWorks model was imported. After inputting the parameters on the model and applying our force, the simulation was solved and the solutions were analyzed. The parameters inputted for the simulation can be seen below in Figure 8.

Ni-Co alloy layer	CBN
• **E**: 169.6181GPa • **v**: 0.31 • **Ni-ρ**: $8.88 \times 10^3 kg/m^3$ • **Co-ρ**: $8.9 \times 10^3 kg/m^3$ • **yield strength**: 356.32MPa	• **E**: 909GPa • **v**: 0.121 • **ρ**: $3.4 \times 10^3 kg/m^3$

Figure 8 Parameters for CBN Grit and Bonding Layer

From this software, an accurate bonding-force was obtained and recorded. These recorded values were then inputted into our RSM software explained in the following section.

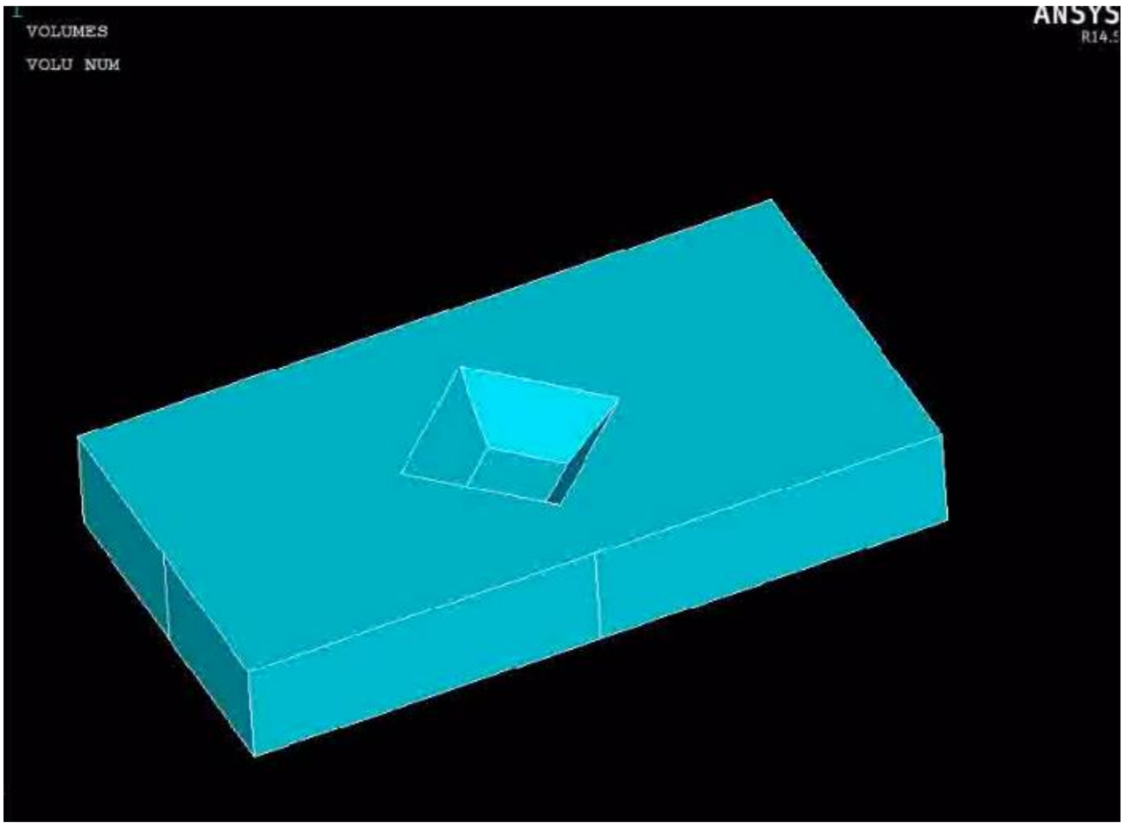

Figure 9 ANSYS: Creation of Contact Pair

Figure 9 above is an example of one of the possible contact pairs between the bonding layer and the CBN grain. Figure 10 shows a completed and meshed model prepared to run the analysis.

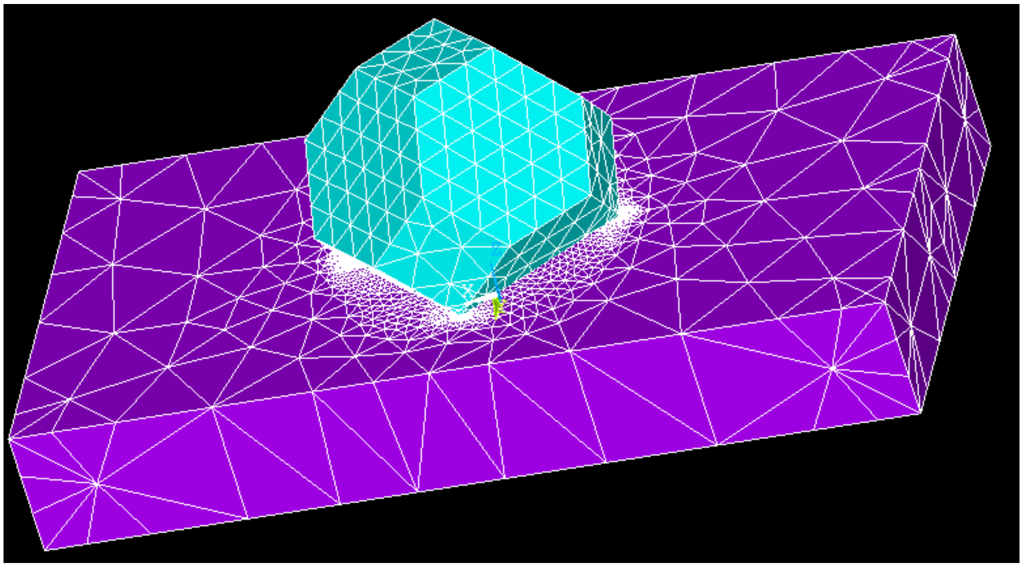

Figure 10 Meshed 3-D Model in ANSYS

Figure 11 shows the stresses on the CBN grain that eventually lead to failure. The force was applied at the top left corner of the grain made clear by the red shading. Figure 11 is the finished ANSYS product.

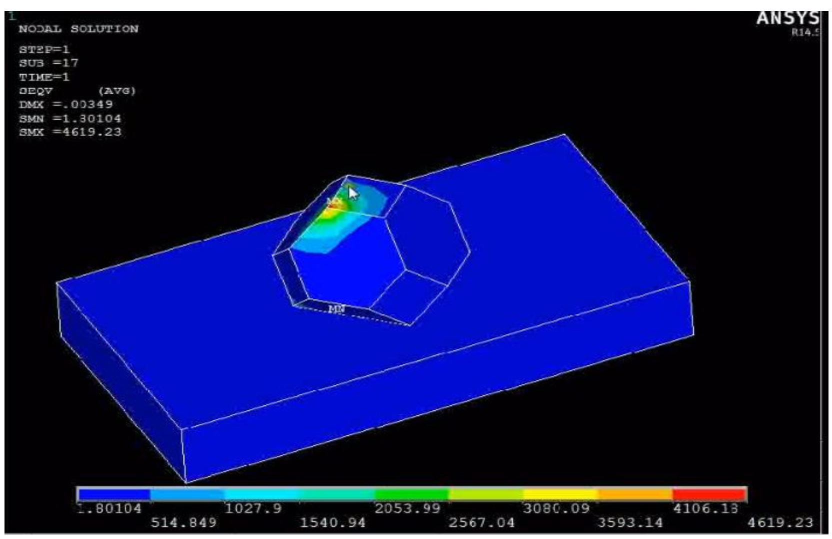

Figure 11 ANSYS Application of Force

Response Surface Method Software

After inputting the bonding forces obtained in ANSYS, the user could create three dimension contour plots of the angles orientation to the stress. From this a series of highest bonding force could be derived. In figure 12 below for each orientation angle listed below the user entered the bonding force solved in ANSYS.

Select	Std	Run	Factor 1 A:X degrees	Factor 2 B:Y	Factor 3 C:Z	Response 1 Bonding Force Newtons
	6	1	60.00	0.00	60.00	
	4	2	60.00	60.00	0.00	
	2	3	60.00	0.00	0.00	
	19	4	30.00	30.00	30.00	
	7	5	0.00	60.00	60.00	
	16	6	30.00	30.00	30.00	
	11	7	30.00	0.00	30.00	
	20	8	30.00	30.00	30.00	
	12	9	30.00	60.00	30.00	
	9	10	0.00	30.00	30.00	
	1	11	0.00	0.00	0.00	
	3	12	0.00	60.00	0.00	
	17	13	30.00	30.00	30.00	
	14	14	30.00	30.00	60.00	
	8	15	60.00	60.00	60.00	
	15	16	30.00	30.00	30.00	
	18	17	30.00	30.00	30.00	
	5	18	0.00	0.00	60.00	
	10	19	60.00	30.00	30.00	
	13	20	30.00	30.00	0.00	

Figure 12 Design Expert: User Enters Bonding Force Values

The optimum orientation angles were solved upon running the RSM model. The 3-D contour plot in Figure 4 provides the X and Y orientation values with the maximum stress as the top of the curve for the Z angle equal to 36.49.

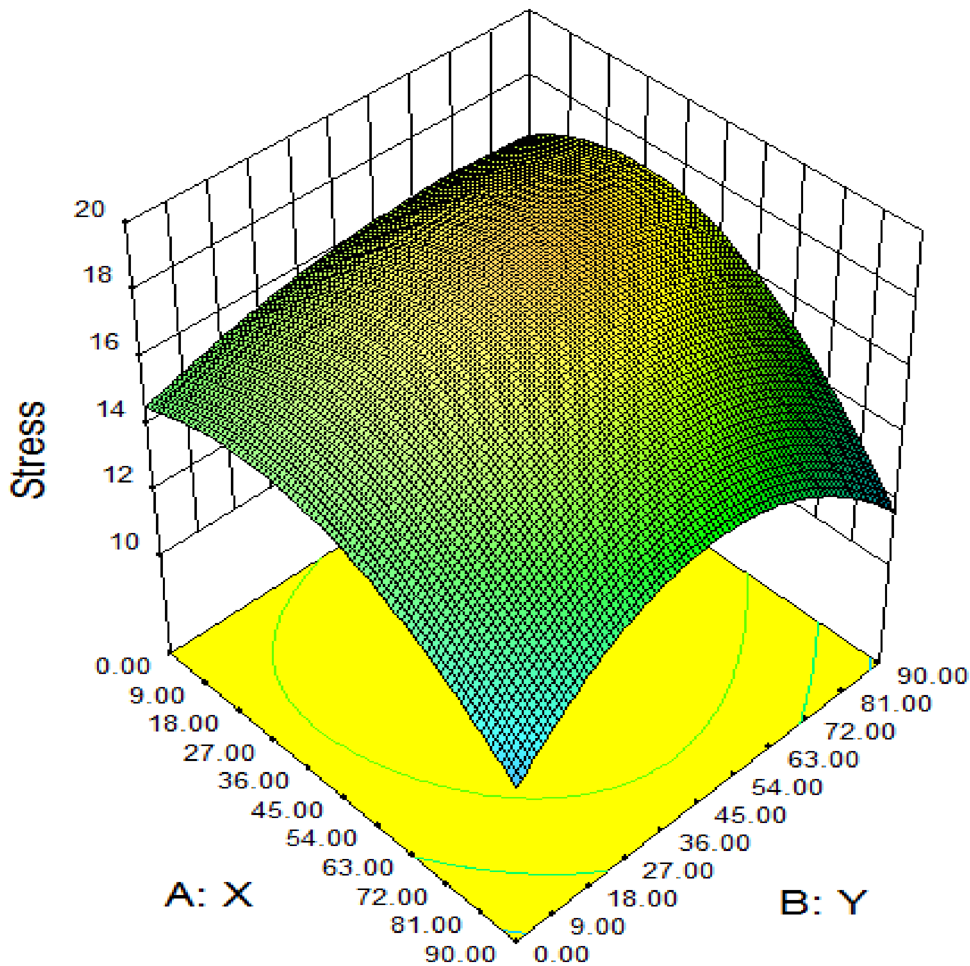

Figure 11 3-D Contour Plot at Z=36.49

Figure 12 gives the range of bonding force as well as a list of solutions with the highest bonding forces. The number one solution occurred at the angle (4.87°, 16.92°, 52.13°) with a bonding force of 4.01261 newtons. The lowest value can be seen in Figure 12 as 1.217 newtons.

Name	Goal	Lower Limit	Upper Limit	Lower Weight	Upper Weight	Importance
A:X	is in range	0	60	1	1	3
B:Y	is in range	0	60	1	1	3
C:Z	is in range	0	60	1	1	3
Bonding Force	maximize	1.21724	4.00661	1	1	3

Solutions

Number	X	Y	Z	Bonding Forc	Desirability
1	4.87	16.92	52.13	4.01261	1.000
2	6.00	30.00	54.00	4.06839	1.000
3	24.27	50.26	55.00	4.24984	1.000
4	34.05	58.72	58.30	4.19824	1.000
5	5.00	5.00	59.00	4.179	1.000

Figure 12 Solutions in Design Expert

In Figure 13 the maximum bonding force is within the value of four lines highlighted in the darker red range.

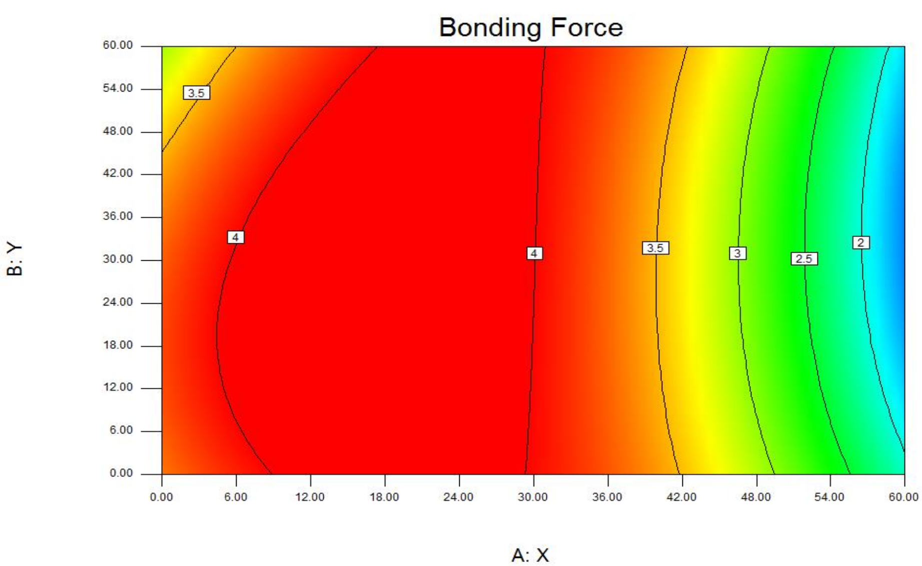

Figure 13 Slice of 3-D Contour at Maximum Bonding Force

Figure 14 above provides each bonding force value in newtons for each tested orientation of the CBN grain.

ANGLE X	ANGLE Y	ANGLE Z	BONDING FORCE
0	0	0	3.5008
0	30	30	3.1779
0	0	60	4.0066
0	60	0	3.8438
0	60	60	3.2352
30	0	30	2.8374
30	30	0	2.3848
30	30	60	3.9679
30	60	30	2.8123
60	0	0	3.5155
60	0	60	2.1685
60	30	30	1.2172
60	60	0	1.9985
60	60	60	2.1112

Figure 14 Bonding Force (N) for Each Orientation Angle

Conclusions and Recommendations

The completion of the three step methodology from SolidWorks models to ANSYS bonding force to Design Expert analysis yielded the highest bonding force of 4.01261 newtons occurring at the X, Y, Z angles of (4.87°, 16.92°, 52.13°).

The impact of this project could allow conditioner pads for the CMP process to last longer. More resilient pads could lower the cost and increase productivity during the planarization process.

Despite the fact this project generated a list of possible solutions in addition to the highest given above, only three variables being the lead, orientation, and shear angles were changed. The bonding layer thickness, grain size, grain shape, pressure of pad, and diameter were kept constant. Future projects should isolate other variables to provide insight into the best possible combination to provide the highest bonding force. After isolation, more than one variable or set of variables should be tested in different combinations. These combinations should be tested in a FEM software similar to the ANSYS software.

After FEM analysis has been completed for all variables and multiple promising combinations with high bonding forces have been compiled, the theory should be put into practice by creating a physical model. The physical model designed with certain parameters could then be experimented on to obtain actual values to compare to the FEM theoretical values. This information provides insight into the accuracy of the FEM model which could lead to modifications beneficial to future FEM use.

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